Final 40-50 T Cooling

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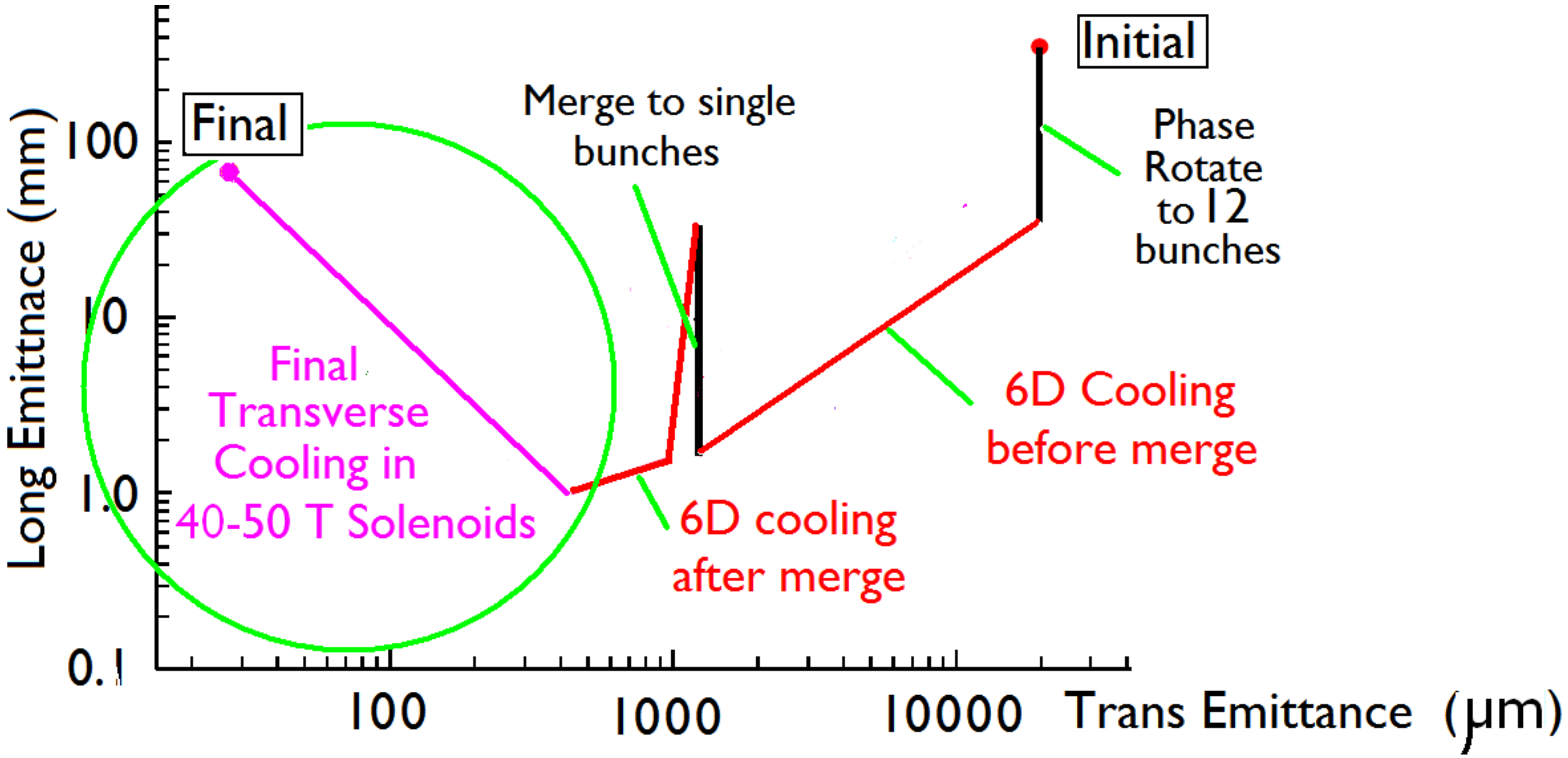
Cooling Scheme



- IN: $\varepsilon_{\perp}$=400 μm $\varepsilon_{\|}$=1.1 mm Goal: $\varepsilon_{\perp}$=25 μm $\varepsilon_{\|}$=72 mm
- Transmission goal: 70%

Minimum emittances vs. B and Energy

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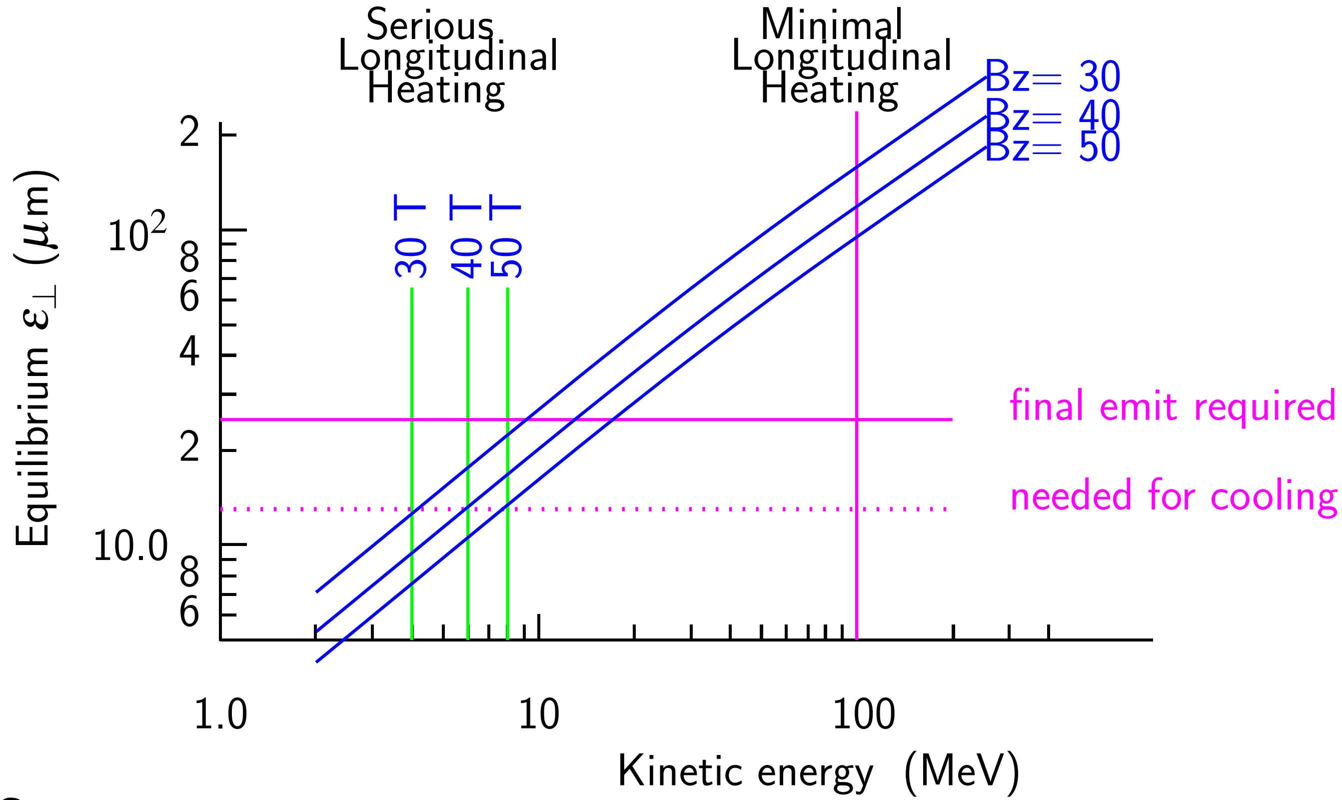
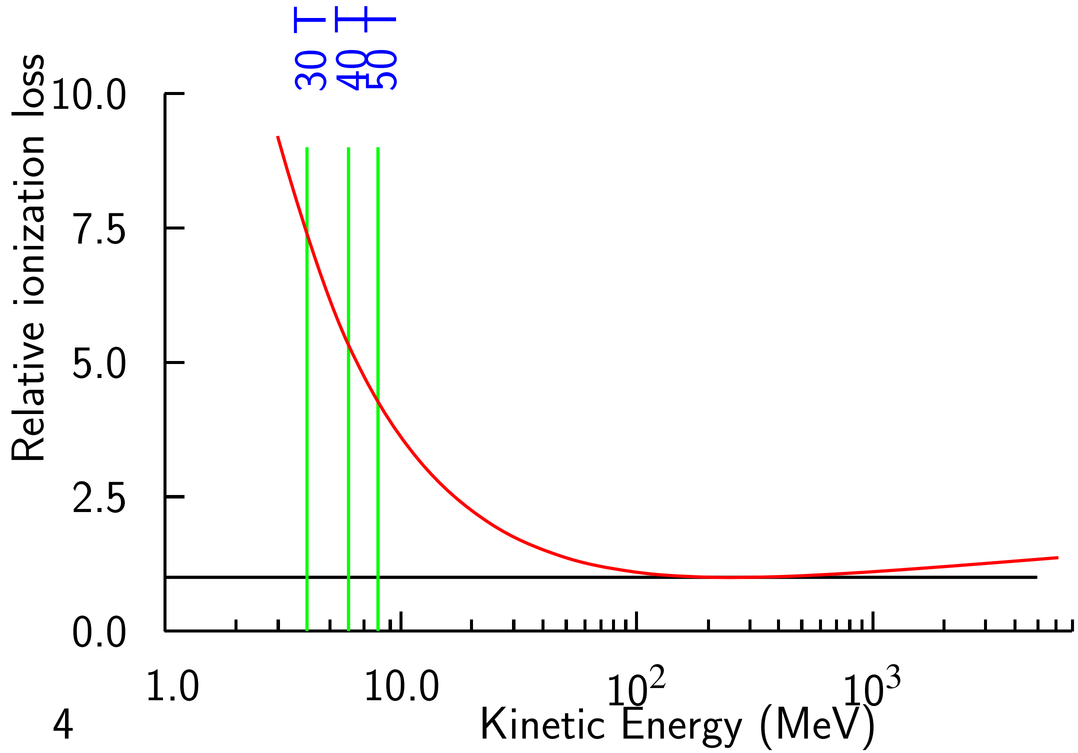


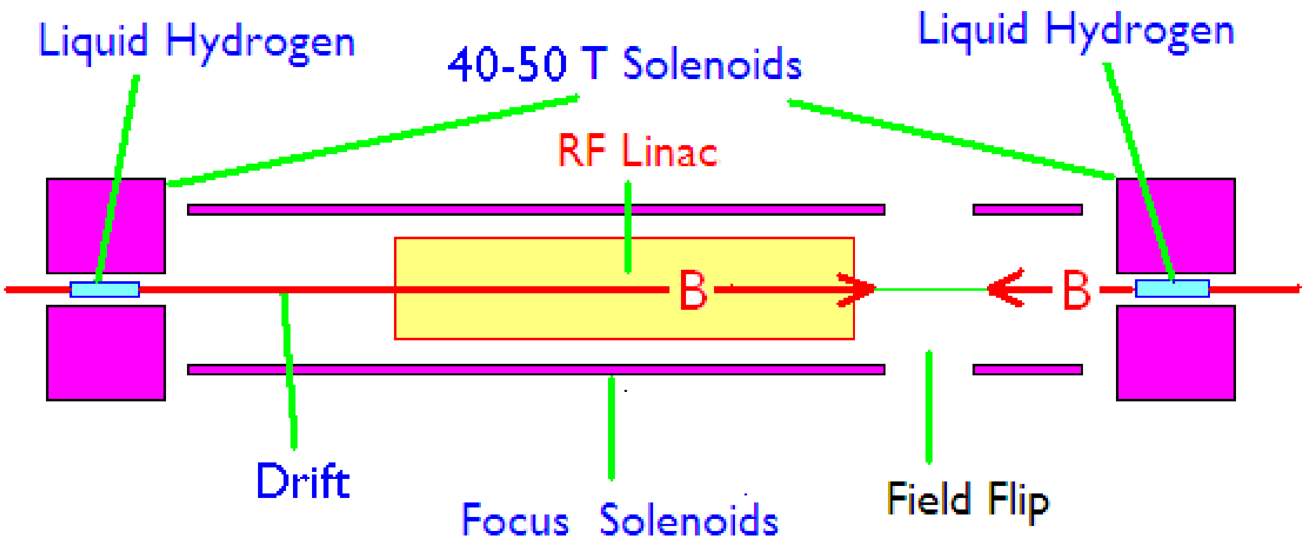
- At lower energies
  - Focusing stronger & Energy loss greater
- Cooling to any emittance, with any B, if energy is low enough!

Energy loss



- But the lower the energy, the steeper the slope of dE/dx vs. energy
- And the faster dE/E rises: giving worse longitudinal heating

One stage



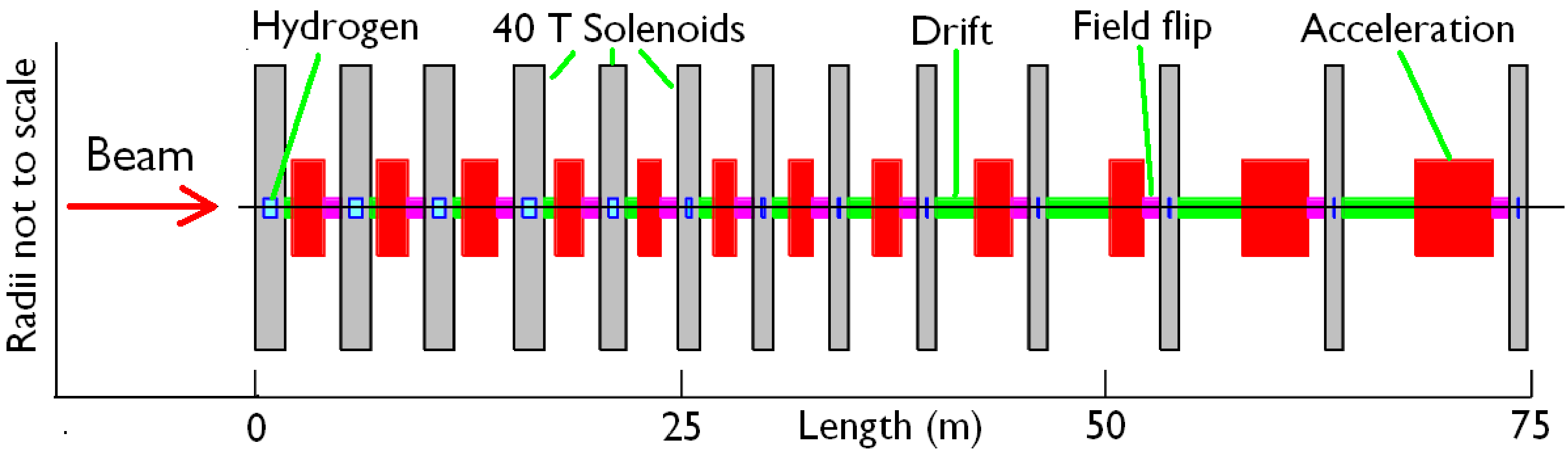
- Cooling limited to $\approx$ 20% before dE/dx $\longrightarrow$ excessive
- Drift needed to phase rotate to new longer bunch and ok dE/dx
- Field must be reversed to avoid angular momentum build up

Design & optimization

- For each stage, with starting emittances from last stage, choose
  - Initial energy
  - Initial energy spread
  - hydrogen length
- Run ICOOL only for length in hydrogen with fixed field
- Assume no dilution from match & re-acceleration (justified later)
- Calculate decay in length for phase rotation & acceleration
- Optimize for:
  - A minimum slope of $d\varepsilon_{\parallel}/d\varepsilon_{\perp}$ to achieve or beat goal emittances
  - A reasonable $\Delta\varepsilon_{\perp}/\varepsilon_{\perp}$ to keep down number of stages
  - Moderate particle loss for given emittance reduction

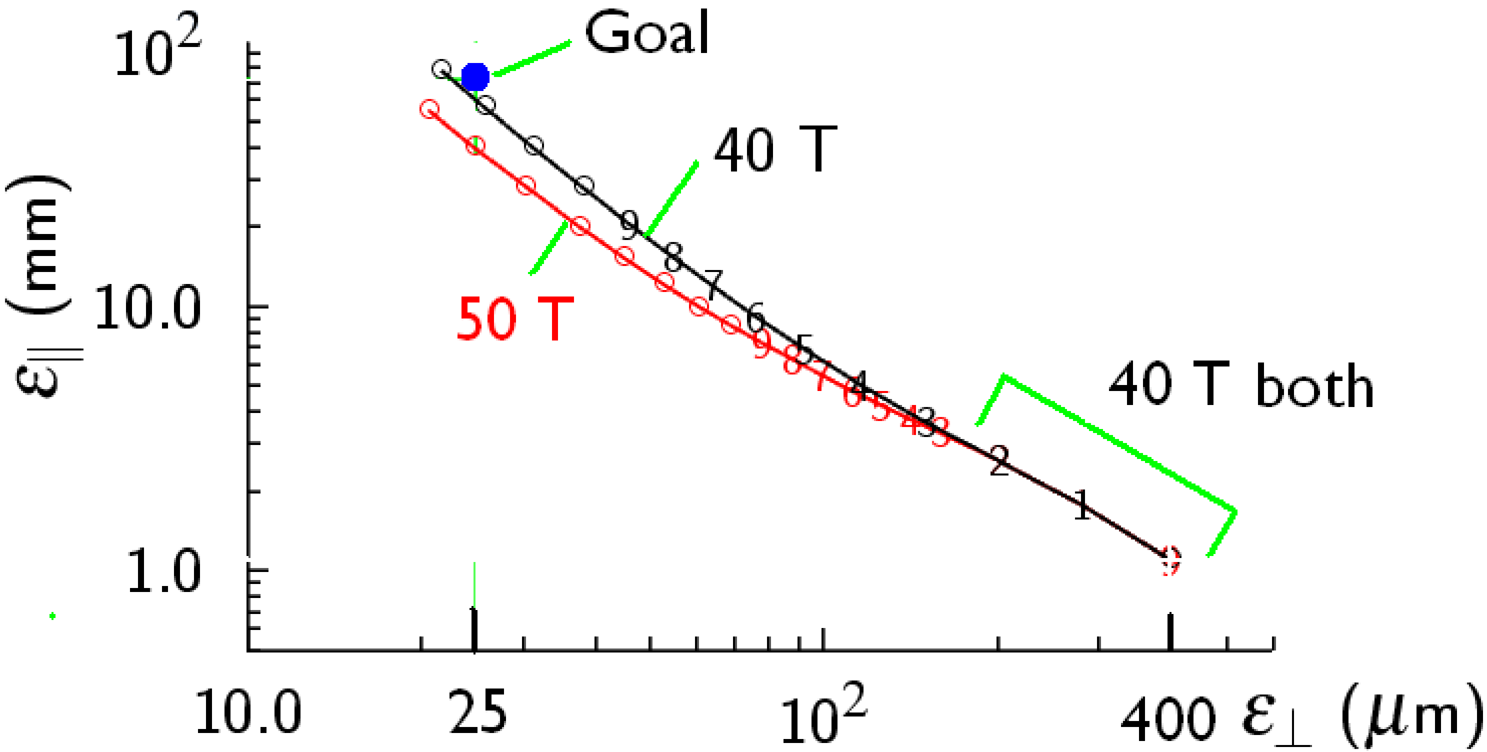
Example solution

13 stage, all magnets at 40 T



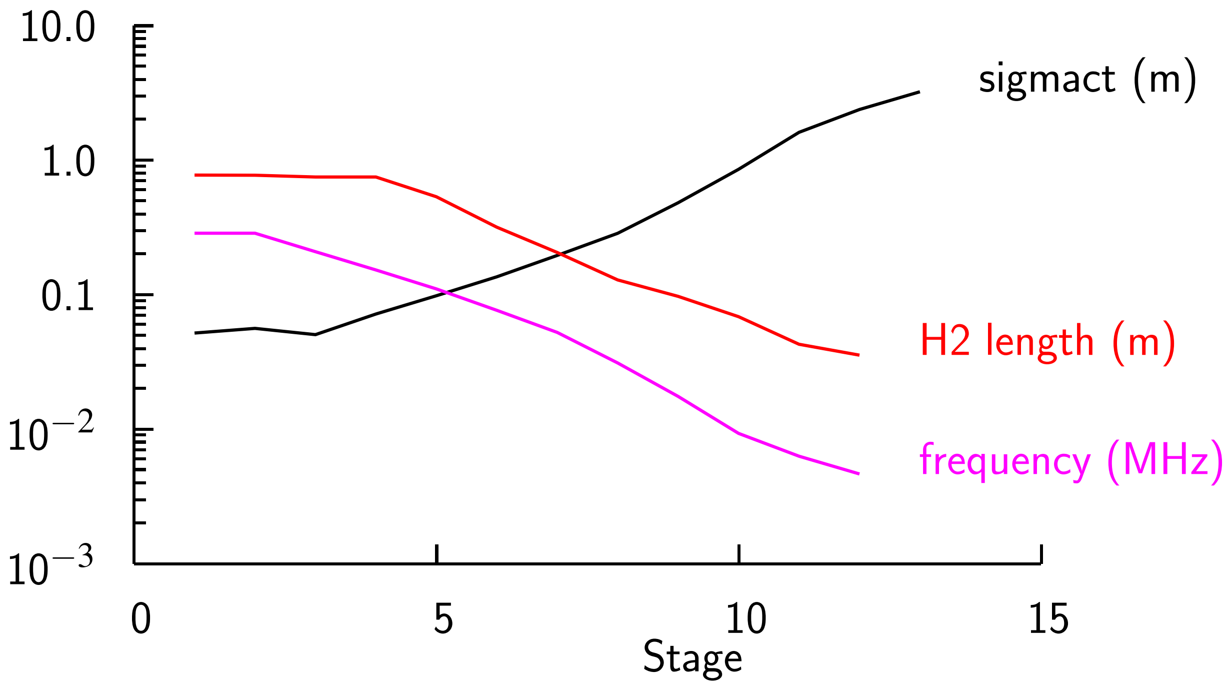
- Each stage cools transverse emittances by ≈ 20%
- Longitudinal emittance increases by a similar amount
- A reasonable dp/p requires growing bunch lengths

Simulated performances



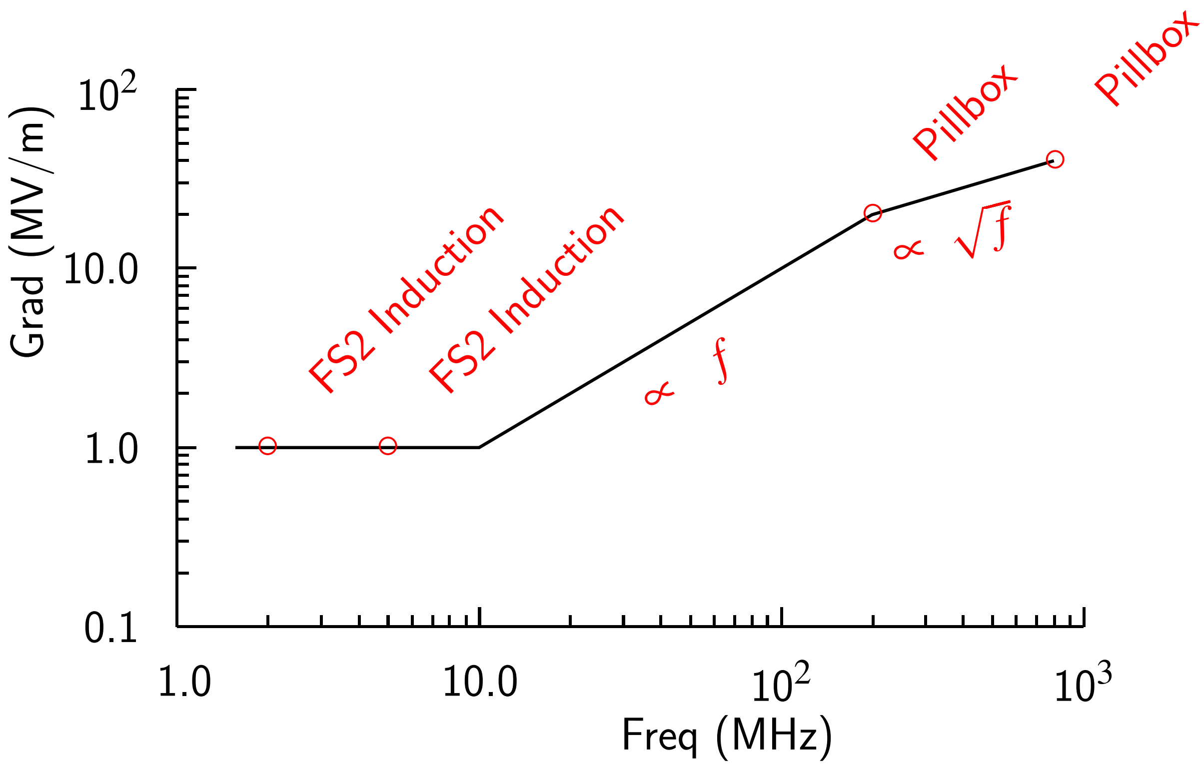
- 40 T solution meets emittance goals
- 50 T solution provides greater margin and/or improved performance
- Extrap. suggests 30 T would cause only moderate performance loss

Details 1



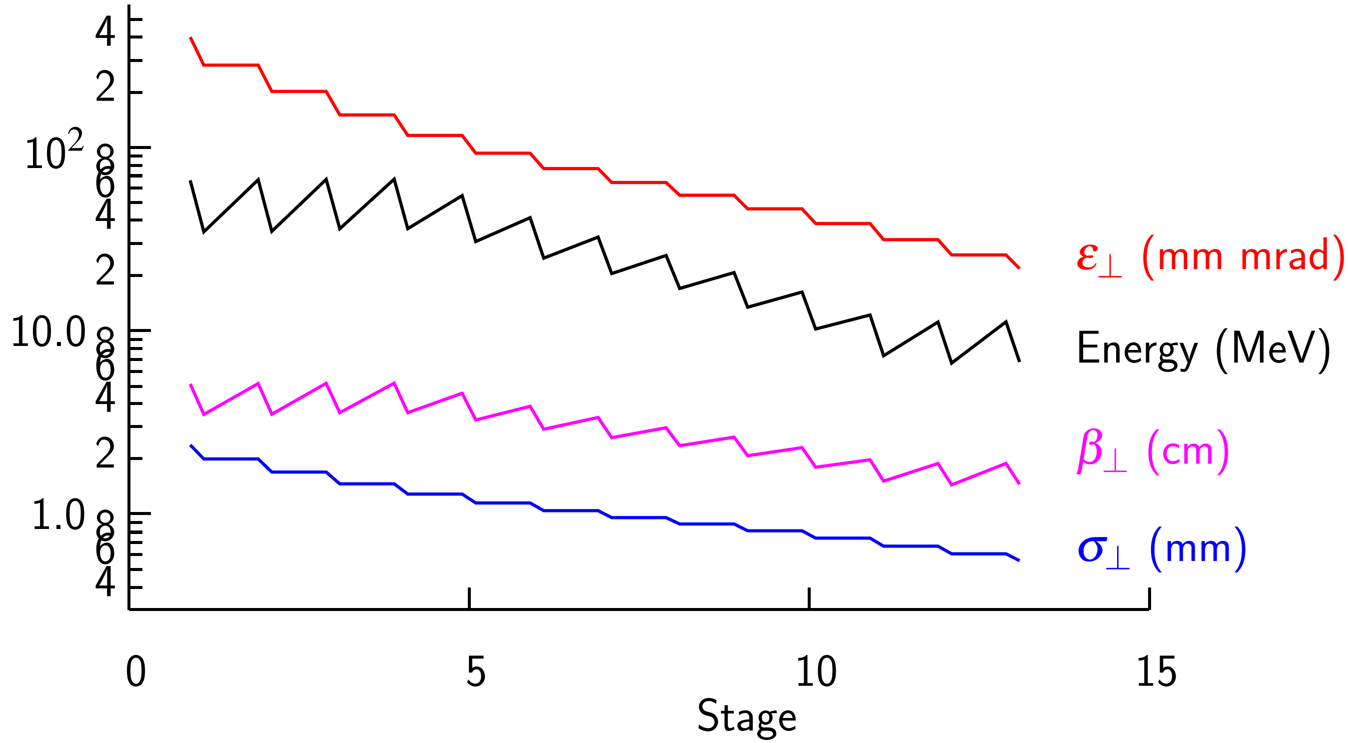
- Hydrogen and magnet lengths fall from 75 cm to ≈ 4 cm
- Bunch rms length rises from 5 cm to 300 cm
- RF frequency falls from ≈ 300 MHz to ≈ 4 MHz

Assumed gradients



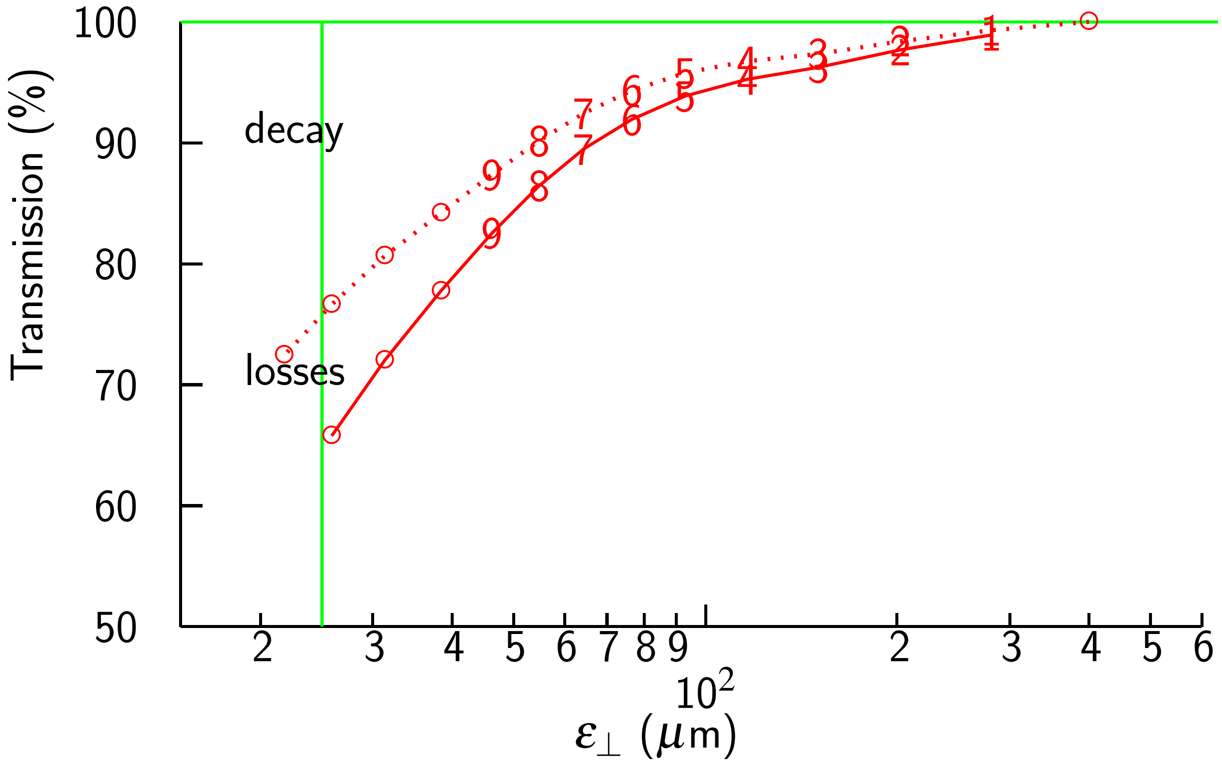
- Only induction linacs give required gradients for long bunches

Details 2



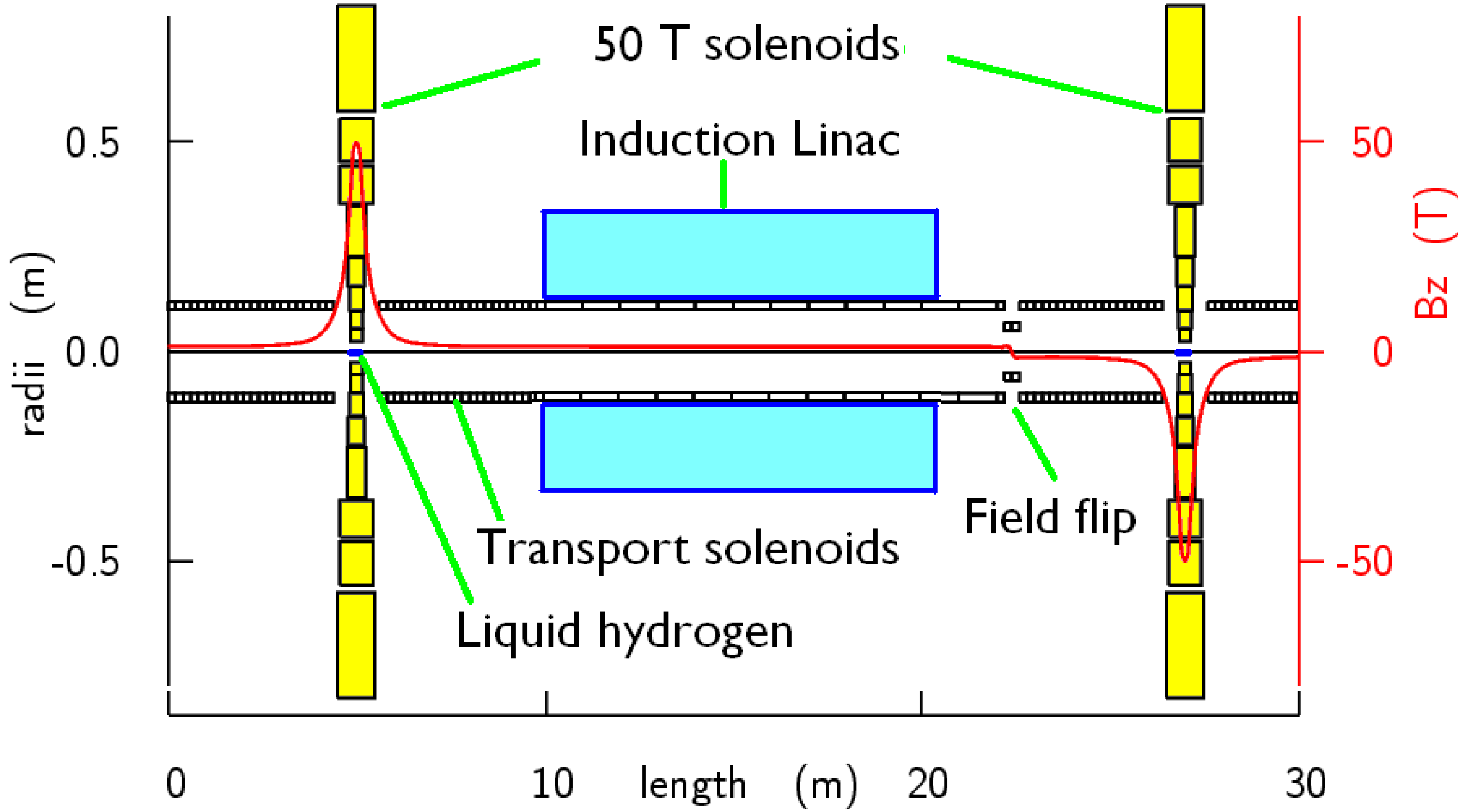
- Beam rms radii fall from 2 cm to $\approx$ 6 mm
- Beam energy falls from 70 MeV (135 MeV/c) to $\approx$ 6 MeV

Simulated transmission



- Losses a little above goal: 65% vs. goal of 70%
- More than made up by other systems (discussed later)

Example of matching & re-acceleration

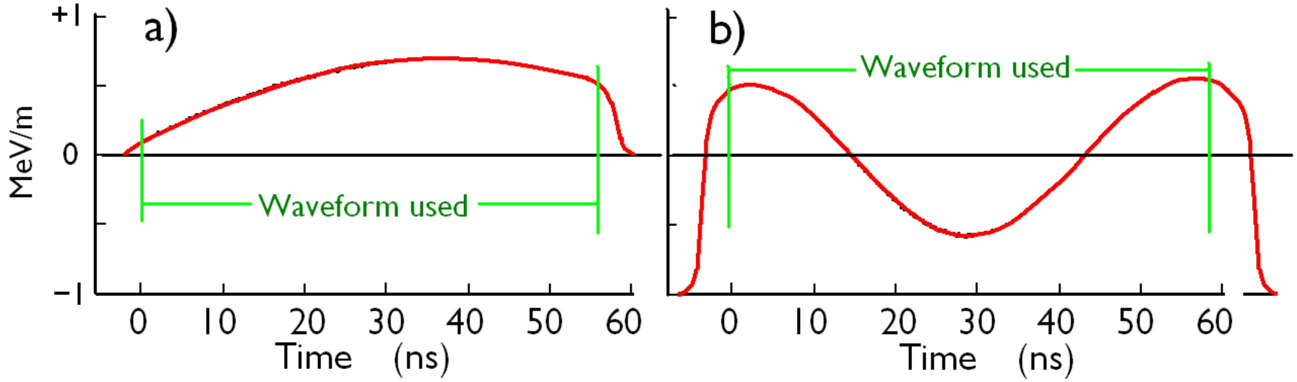


- This example is from the 50 T sequence
- It includes the final and penultimate stages

Induction Linac

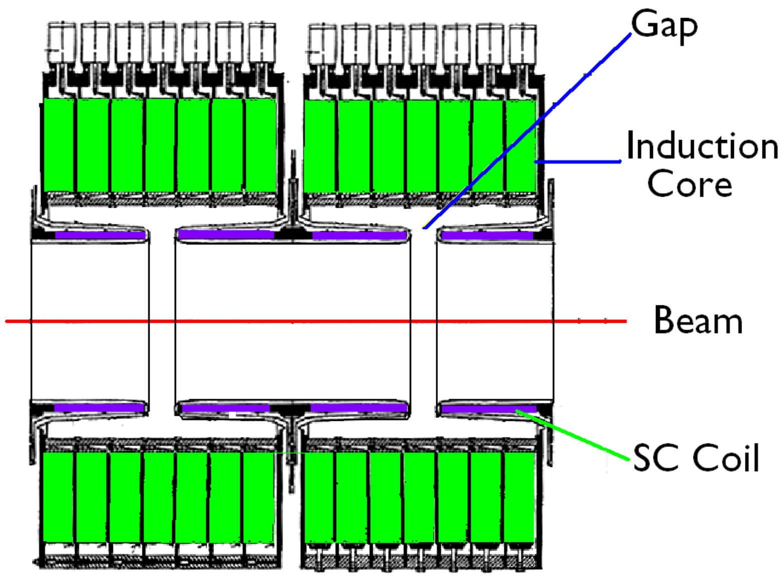
Induction Linac

Waveforms

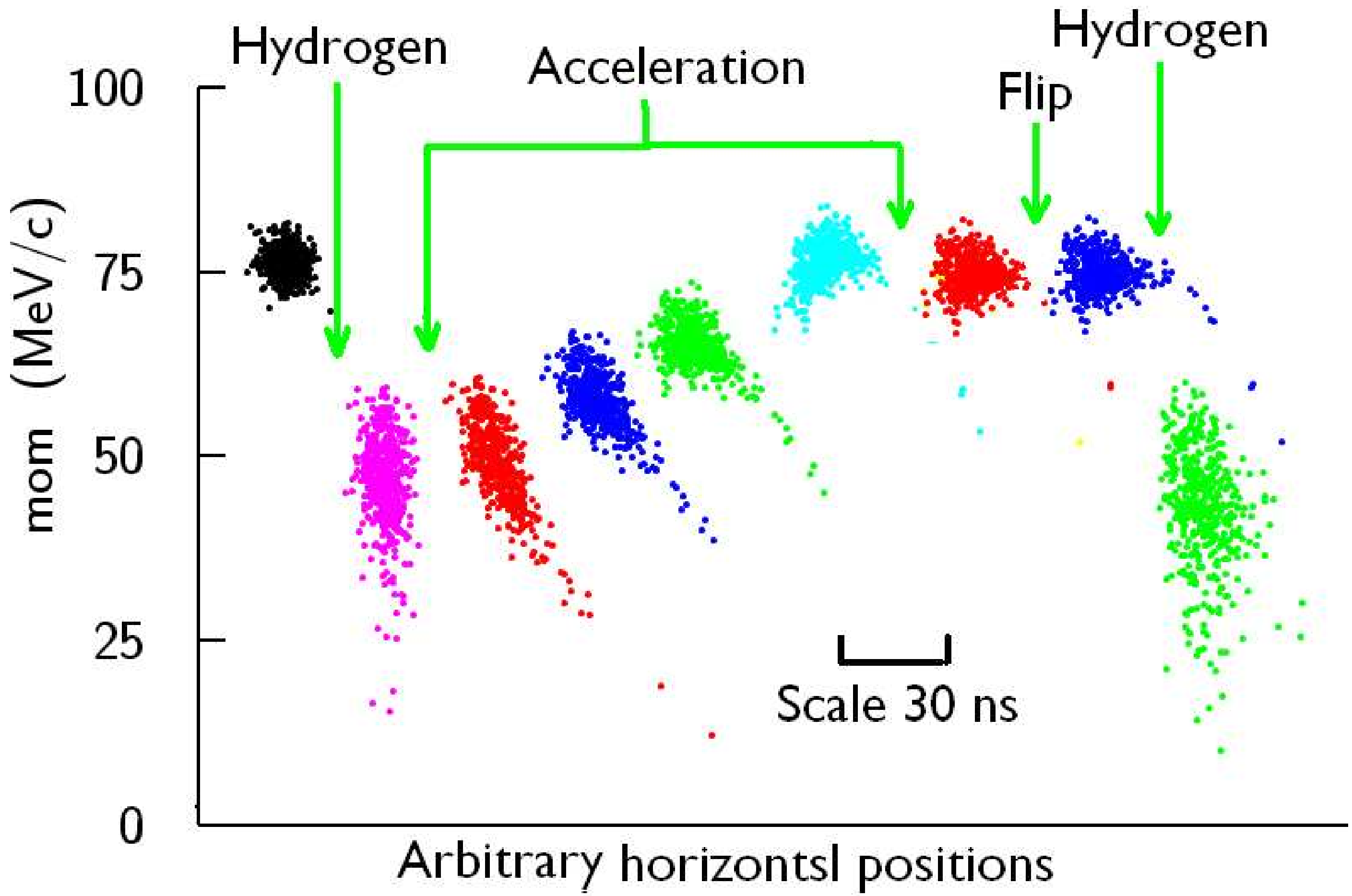


Study II

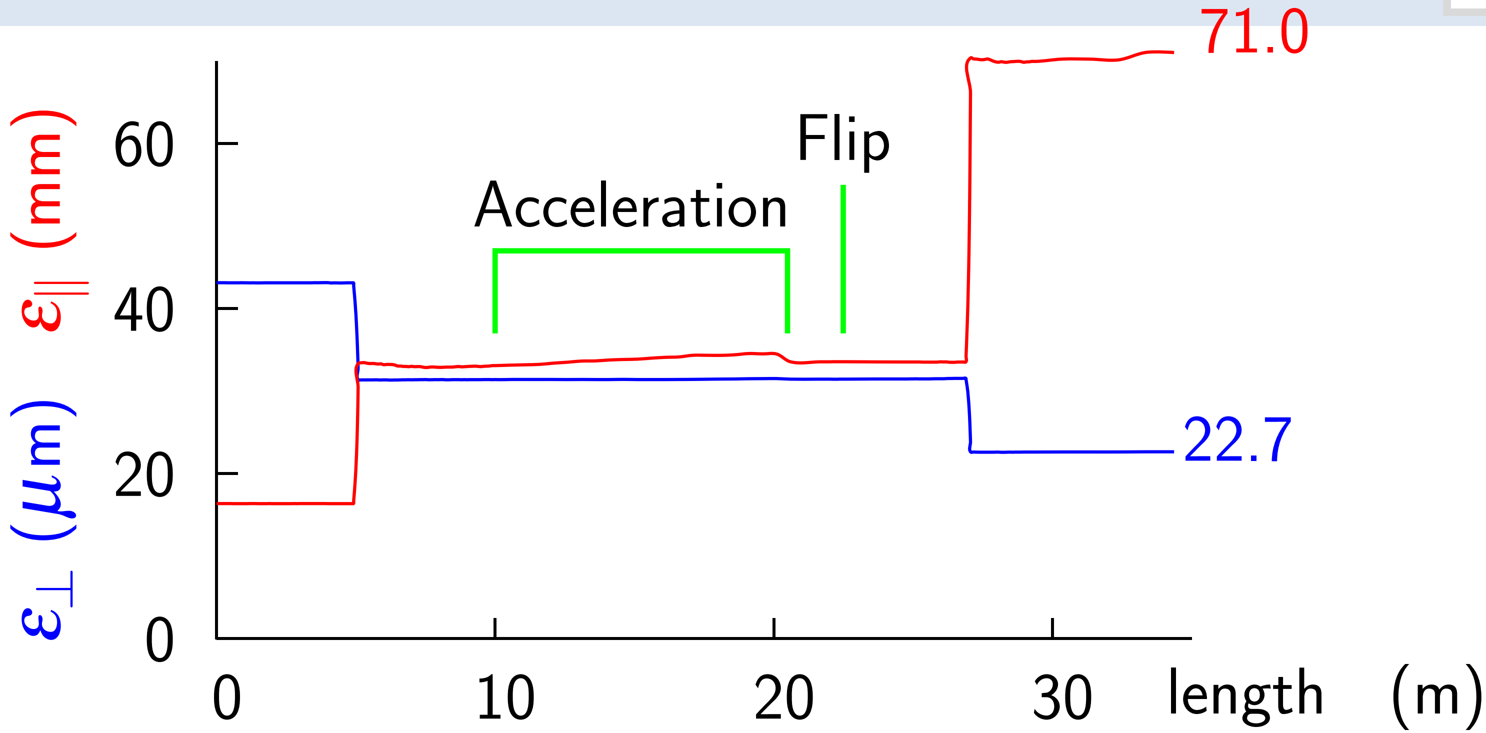
Induction design



Phase space evolution



Emitance evolution



- In match and re-acceleration:

  0.01% $\varepsilon_\perp$ dilution 0.5% $\varepsilon_{||}$ dilution 7.3% loss

- Negligible dilutions justify design assumption above

System Transmission

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Example from recent compilation with 8 GeV protons and MARS 15:

	transmission	cumulative	mu/p
After rotation		1.0	0.219
Best 21 bunches	0.7	0.7	0.153
Charge separation	0.9	0.63	0.138
6D Cooling before merge	0.47	0.30	0.065
Merge	0.88	0.26	0.057
6D Cooling after merge	0.48	0.12	0.027
40 T Cooling	0.65	0.08	0.018
Acceleration	0.7	0.057	0.0125

- 40 T cooling has higher losses than goal
- But made up in production & charge separation
- For 2 10^{12} muons requires 1.6 10^{14} 8 GeV protons/bunch
- Power at 15 Hz: 3.1 MW (cf 4 MW baseline)
- We still have a margin

Other Final Cooling schemes to study

- The object is to achieve lower transverse emittances
  - to allow lower muons/bunch at higher rep. rate
  - easier p driver, less collective effects,
  - less detector background
- Reverse emittance exchange in wedges

  Could be done inside 40 T solenoids

  Not yet simulated
- Emittance exchange at higher energy using septa

  Not yet simulated
- Use of either requires more efficient earlier cooling

TASKS

- Automate optimization of multi-stage systems
- Design sequence using 30 T solenoids and determine consequences
- Simulate full sequence of stages at chosen field
- Study space charge and loading
- Confirm simulations using G4-beamline
- Integrate into full capture-cool-acceleration scheme
  - Design late 6D cooling to match required 135 MeV/c mom.
  - Design initial acceleration of 6 MeV, very long, output bunches
- Demonstrate 40 T solenoid (discussed in later talks)
- Study schemes for lower emittances

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Conclusion

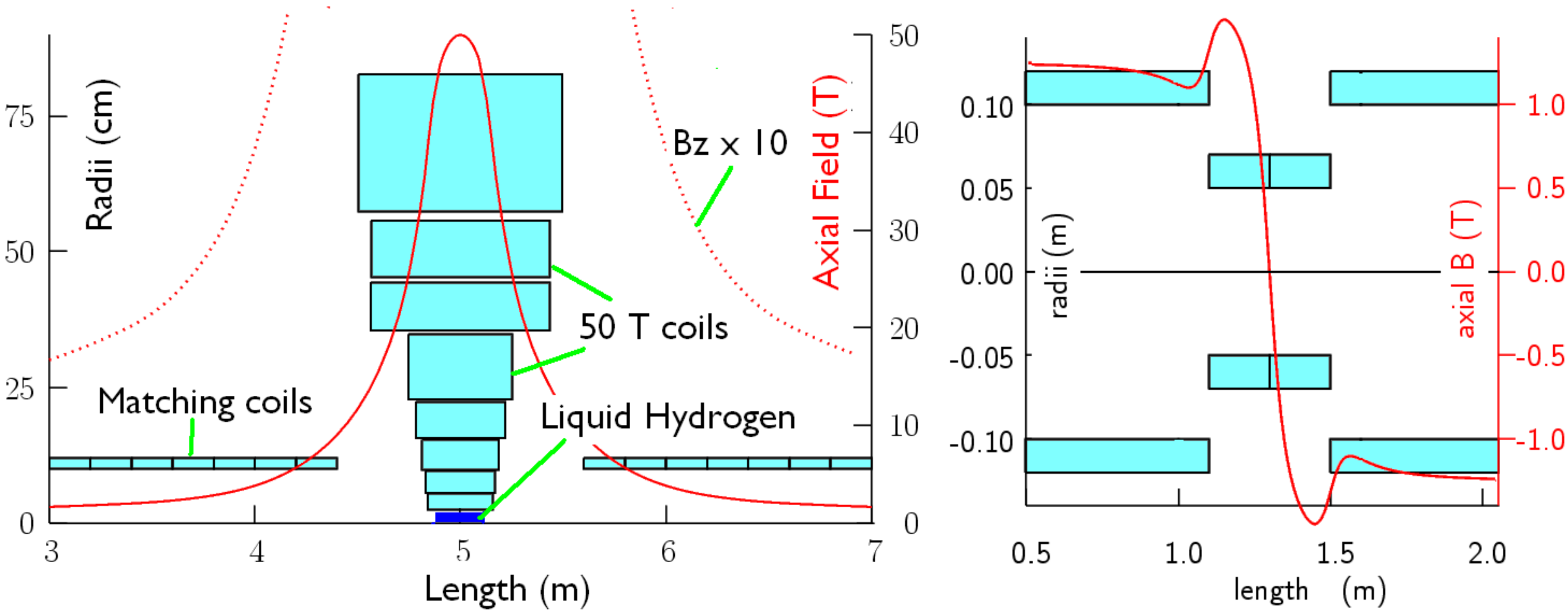
- Sequence of 40 T cooling stages appears to meet emittance goals
  - Sequence of 50 T solenoids would give more margin, lower emittance and somewhat improved luminosity
  - Extrap suggests 30 T would cause only moderate performance loss
- Lower (65% vs. 70%) simulated transmission appears more than compensated by gains elsewhere
- Simulation of matching and re-acceleration between last stages showed negligible dilution and acceptable transmission

- But much work still to be done

Appendices

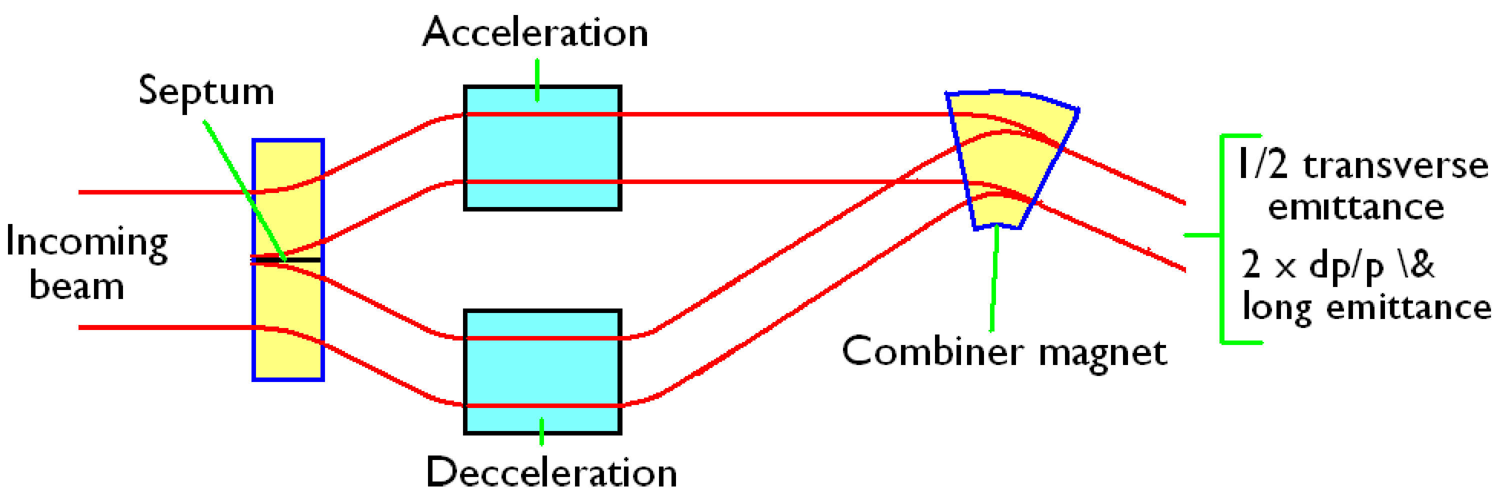
- Details of matching between final 50 T solenoids
- Septum emittance exchange
- Reverse emittance exchange

Detail of 50 T matching & field flip



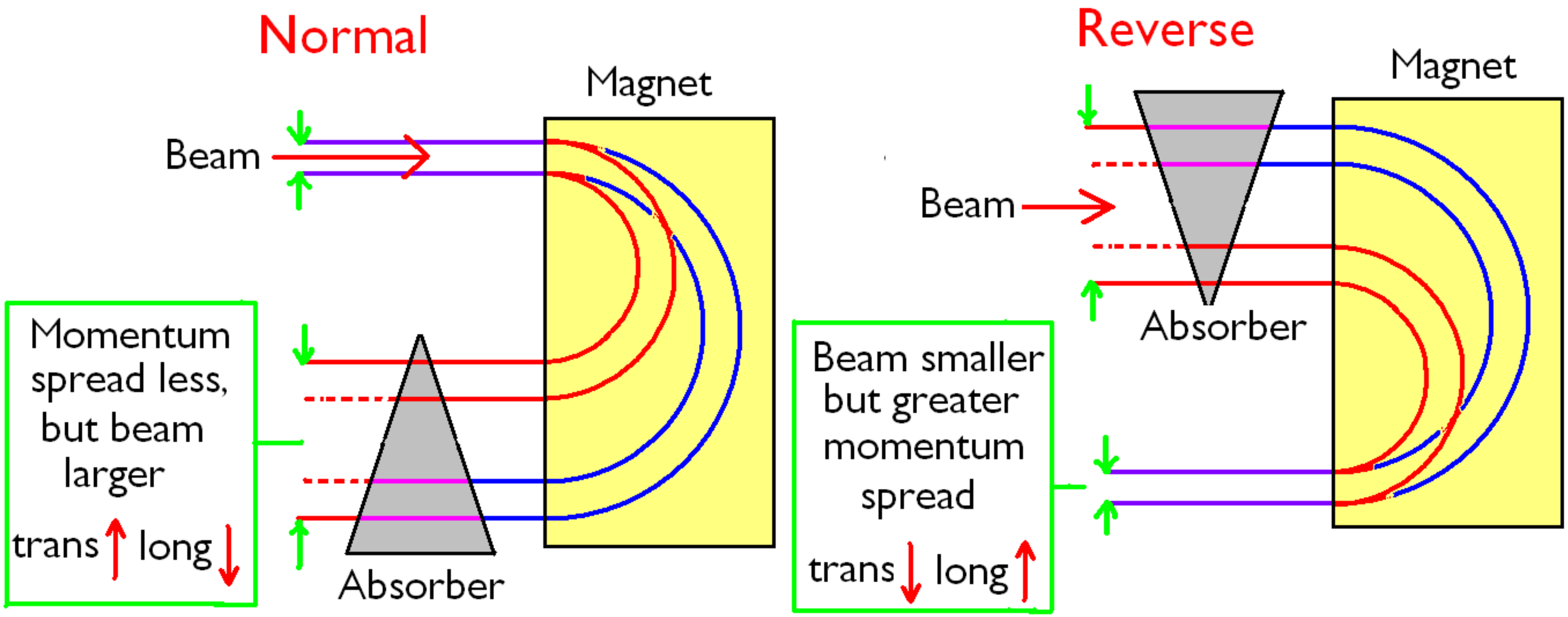
- ❍ Adiabatic match from 50 T $\longrightarrow$ 1.25 T
- ❍ Rapid field flip with beta matching

Septum emittance exchange



- Should be done also in orthogonal direction
  or use septa in x and y followed by 4 channels
- Can be done at any energy
- Will be less efficient than 40-50 T cooling for $\varepsilon_\perp > 25\ \mu$m
  but, in principle, will work for any emittance

Reverse emittance exchange in wedges



- Still requires low beta from strong solenoid
- But lowers emittance faster, is less affected by scattering
- Can exchange to lower emittances